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What are learning about the inner disk from infrared long baseline interferometry

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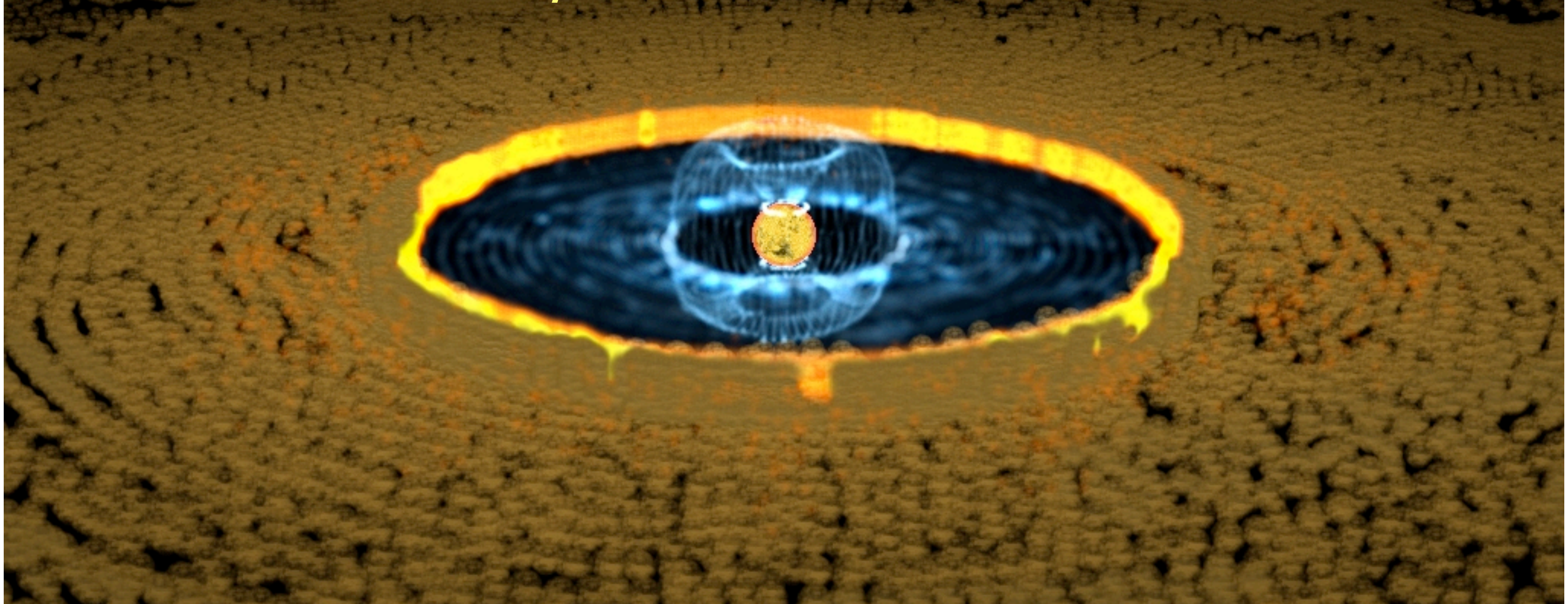


Planet Formation Processes & the Development of Prebiotic Conditions
Pasadena – March 18-21 2008

Image credit: Luis Bellerique (UNAM)

Why optical interferometry of circumstellar disks?

- ✓ **Spatial Resolution**:
  - $\lambda/2B$ = 4mas for B=100m λ=2.2μm or 0.4 AU @ 100pc
  - $\lambda/2B$ = 21mas for B=100m λ=10μm or 2 AU @ 100pc

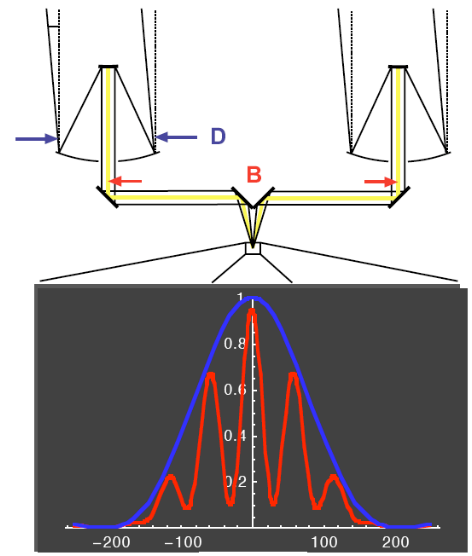
  - Measure a number of fringe amplitudes $V(u,v;\lambda)$
  - Different λs probe different emission mechanism (and different resolution).
  - Model fitting using these $V(u,v;\lambda)$

- ✓ These measurements place very powerful constraints on the **spatial distribution** of material:

  - Break the degeneracies inherent to SED modeling alone.

- ✓ Help establish the morphology and physical conditions of the dust & gas, from near the star to few AU:

  - **initial conditions for terrestrial planet formation**



$$\hat{V}_\lambda(u,v) \overset{\text{Fourier Transform}}{\Leftrightarrow} I_\lambda(\alpha,\beta)$$

Measured visibilities at spatial frequencies (u,v) given by source-baseline geometry.

Object brightness

What we are learning

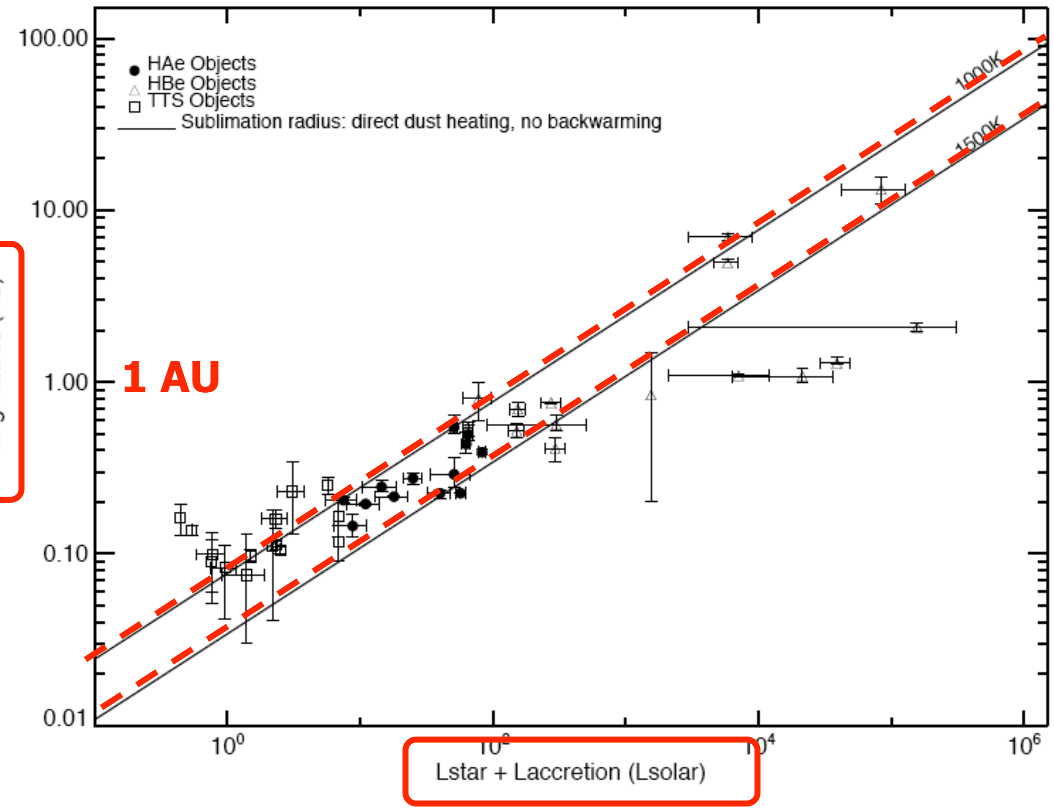
- Characteristic near-IR sizes
  - ✓ Location of disk inner dust edge
  - ✓ Motivated new class of models (“puffed-up inner rim”)
- Characteristic mid-IR sizes
  - ✓ Constraints on flaring models
- Spectrally resolved mid-IR interferometry
  - ✓ Dust disk mineralogy & radial gradients
- Spectrally resolved near-IR interferometry
  - ✓ Inner gas
- Bonus material:
  - ✓ New hot dust population in the HZ

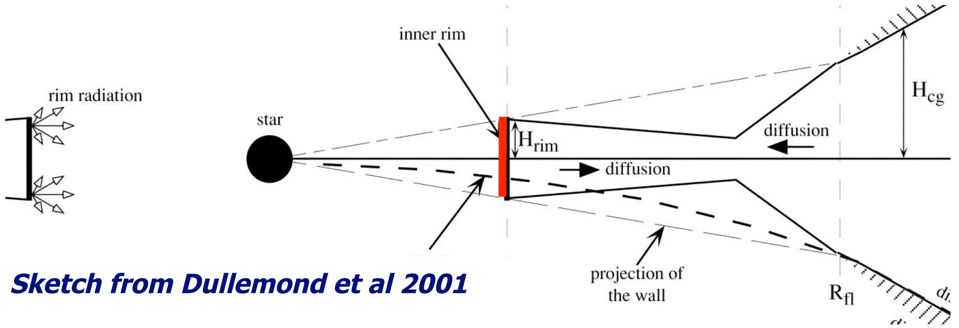
The inner dust disk: location

- The NIR disk sizes measured largely follow the inner dust sublimation radii; these results played a crucial role in motivating a new class of models for the inner dust rim.
- Discrepant objects (some TTaus & high L objects) and scatter in the Lstar - NIRSize relation is being actively investigated, by adding additional physical processes (scattering, thermal gas emission…)

See the review by Millan-Gabet et al. 2007 in Protostars & Planets V

Most data from KI, also IOTA & PTI

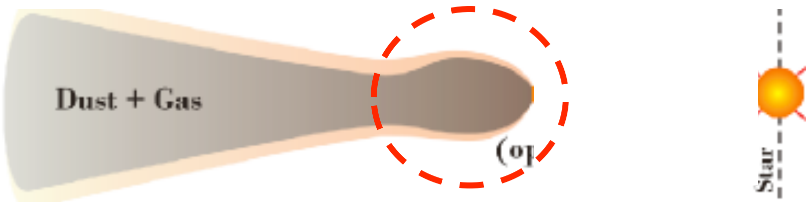




Sketch from Dullemond et al 2001

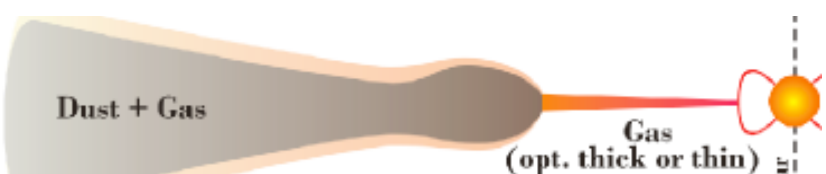
The inner disk: shape

- The low Closure Phases measured (IOTA) indicate a surprisingly high degree of centro-symmetry, favoring very rounded inner dust rims (expected physically e.g. Isella 2005)



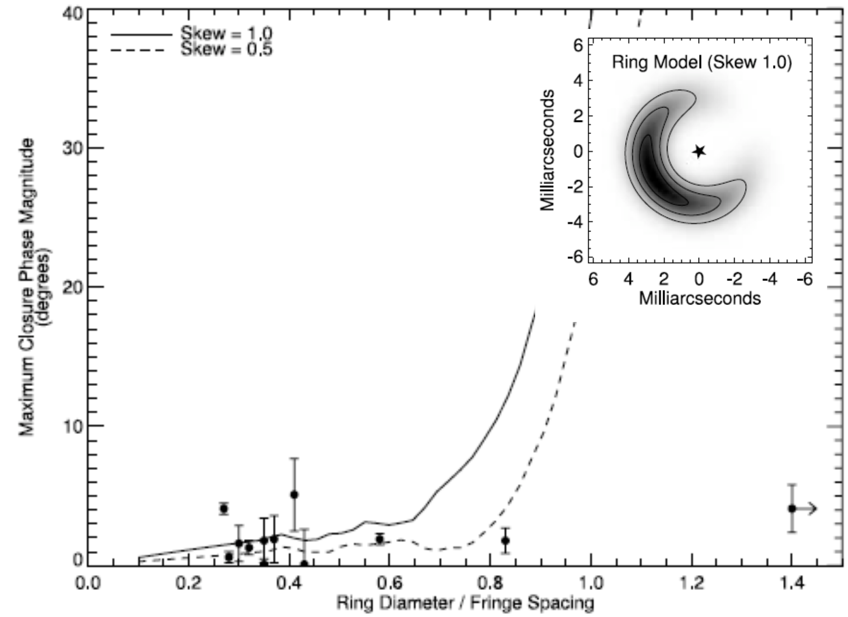
- The very low visibilities measured by the CHARA longest baselines (~300m) cannot be reproduced by detailed models of inner dust rim (they cannot be made smooth enough).

- Best explained by adding NIR emitting gas inside the dust sublimation radius.



Sketch from Kraus07

Monnier, Millan-Gabet, Berger, Traub et al, ApJ, 2005



Tannirkulam, Monnier, Millan-Gabet et al., ApJ, 2008

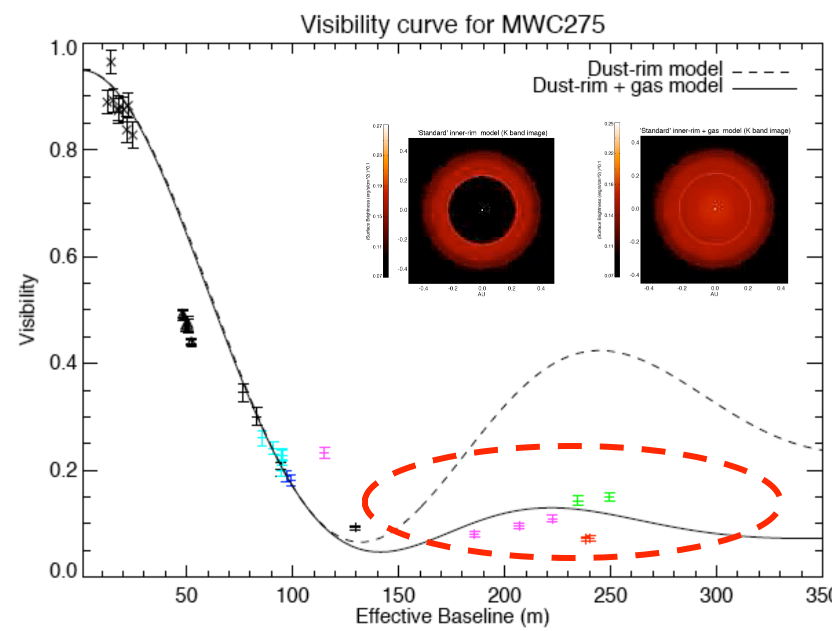
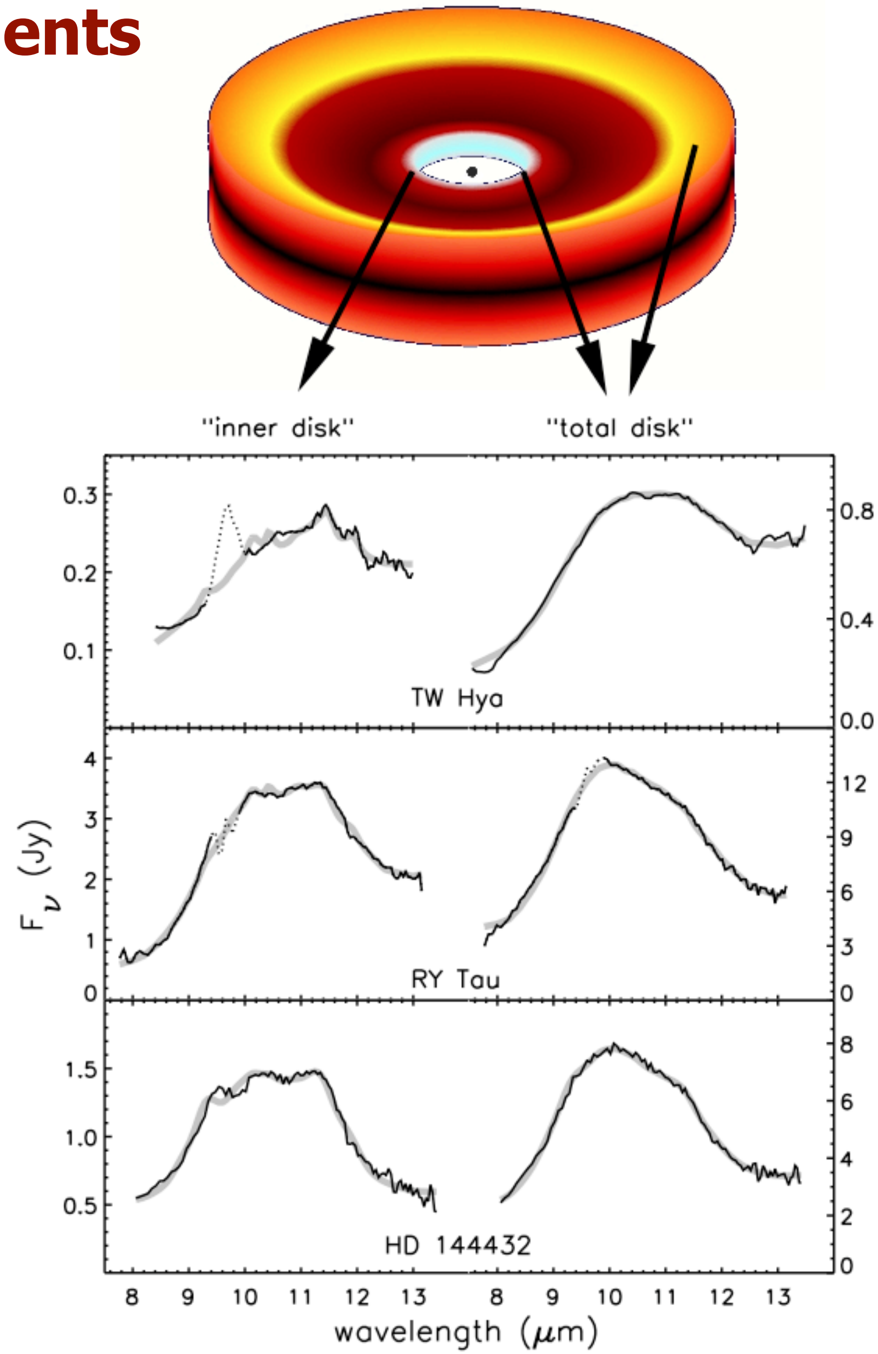


Figure from R. van Boekel

Dust mineralogy & radial gradients

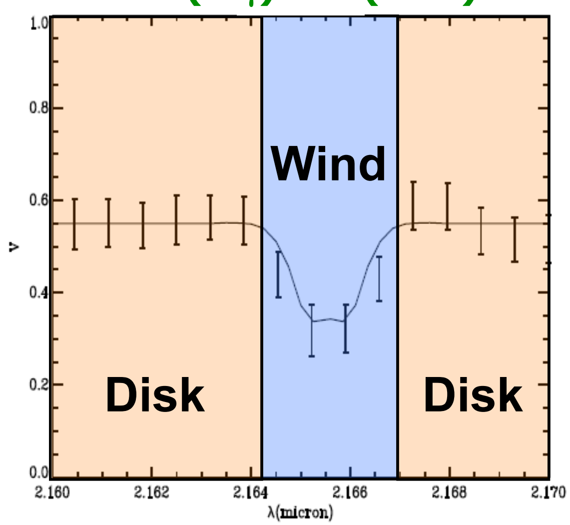
- Many young disks resolved by VLTI/ MIDI (mid-IR instrument w. spectral resolution).
- mid-IR sizes generally agree with flared disks models, and correlate with degree of disk flaring (Leinert 2004).
- Dust mineralogy gradients:
    - higher crystallinity fraction in inner disk (~1-2 AU) compared to outer disk (~2-20 AU).
    - inner disk is highly crystalline well before onset of planet formation.
    - small grains less abundant in inner disk.



Interferometry of gas spectral lines

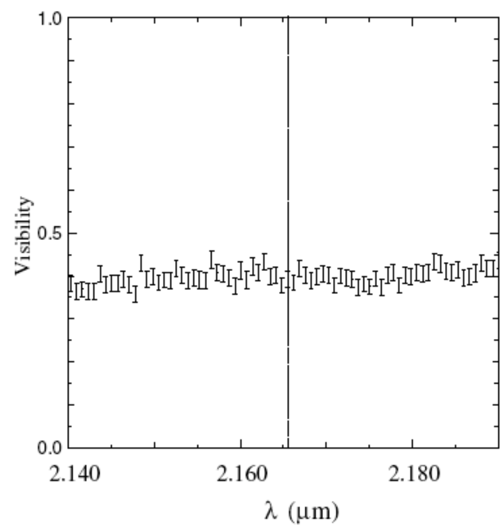
- Emission lines are used to infer the physical properties of CS gas, and to constrain its geometry & dynamics. Their exact origin, however, is not known.
- Low-medium spectrally & spatially resolved visibility measurements (KI, VLTI/MIDI, VLTI/AMBER) provide powerful additional constraints on the location of the gas emission.
- H-gas lines have been detected, and can be found to arise at spatial scales that are larger, smaller, or same as the (dust) continuum: accreting or outflowing components, perhaps depending on the relative importance of Lstar vs. Lacc.
- Also detection of H2O vapor (Eisner07) and CO gas (51 Oph - HBe, Tatulli08).

V(Brγ)<<V(cont)



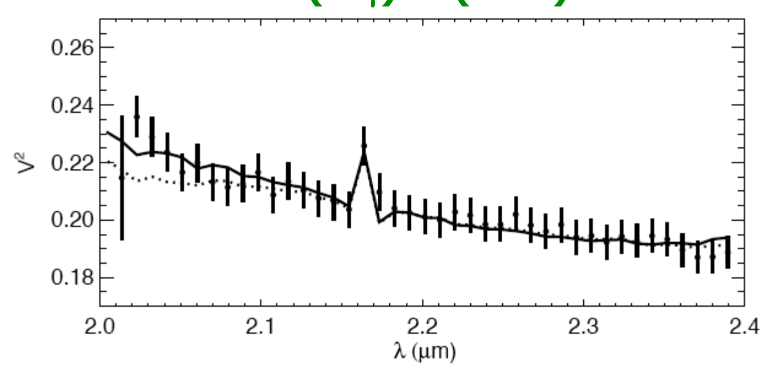
MWC297 HAe - Stellar wind (Malbet05)

V(Brγ)=V(cont)



HD104237 HAe - Base of disk wind (Tatulli07)

V(Brγ)>V(cont)



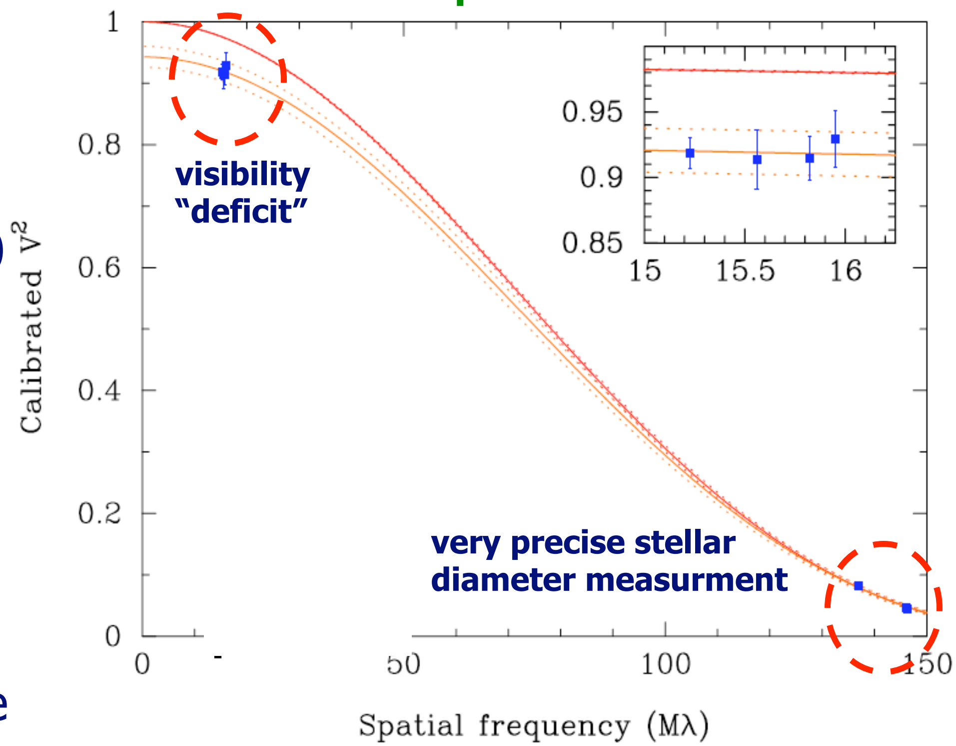
MWC480 (HAe) - Hot inner gas (Eisner07)

decreasing Lstar

Debris Disks Systems - Hot Dust in Exo-Zodi Clouds

- Observations (IRAS, Spitzer, JCMT) have established the existence of debris disks of "second generation" dust; primarily distant 10s-100s AU cold (50K) dust (Kuiper analog).
- Much less is known about warmer (300K) dust near the habitable zone.
- Presence of such exo-zodi clouds at levels > 10 SSZ would prevent detection by planned Terrestrial Planet Finder missions.
- Spectrophotometric techniques are limited in sensitivity to ~1000 SSZ.
- Nulling techniques (KI, LBTI) will improve to 30-100 SSZ.

Example from CHARA:



Interferometers are now revealing a new population of even hotter close-in dust (few% NIR flux, 1000-2000K, 0.1-0.3 AU, <1um grains, not SS density):

- Vega (PTI, Ciardi01; CHARA/FLUOR Absil06)
- τ Ceti (CHARA/FLUOR, Di Folco07)
- β Leo (CHARA/FLUOR, Akeson poster 057.09)
- more in the CHARA pipeline …

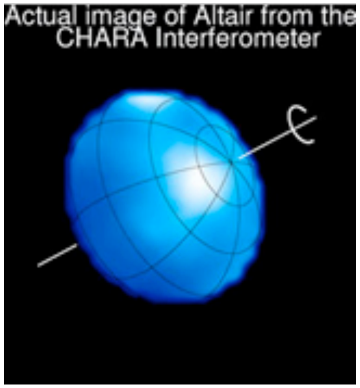
Conclusion

We continue to learn a great deal about circumstellar disks around young stars from long baseline optical (infrared) interferometry. In recent years, greatest progress has come about as a result of starting to use multi-technique (interferometry, photometry, spectroscopy …) and multi-facility (e.g. interferometry observables from more than one instrument and more than one interferometer) datasets, in conjunction with realistic models that take into account all the possible emission components (dust disk, gas disk, wind, envelopes - thermal and scattering emission).

Exciting Prospects …

- **KI:**
  - **Nuller Key Science survey of zodiacal dust around TPF stars (2008).**
  - **ASTRA: Phase referencing for increased sensitivity to disk objects.**
  - **L-band: New (and unique) disk regime.**
- **CHARA: imaging combiners (MIRC+CHAMP, PI: Monnier, U. Michigan).**
- **LBTI: wide field "Fizeau" nulling.**
- **MROI: 10 telescopes => tremendous direct imaging potential.**
- **VLTI: 2^{nd} generation near-IR (VSI) and mid-IR (MATISSE) imaging combiners.**

Teaser: Actual image of Altair from CHARA …



Looking forward to making such images of the inner disks!